

AMERCUY 10N FREQUENCY STANDARD ENGINEERING PROTOTYPE FOR THE NASA DEEP SPACE NETWORK*

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An engineering prototype linear ion trap frequency standard (JITS-4) using $^{199}\text{Hg}^+$ is operational and currently under test for NASA's Deep Space Network (DSN). The DSN requires high stability and reliability with continuous operation. For practical considerations optical pumping and atom state selection are accomplished with a $^{202}\text{Hg}^+$ RF discharge lamp, and the trapped ions are cooled to near room temperature using a helium buffer gas. The standard is closely modeled from earlier research standards JITS-1 and JITS-2 which have demonstrated excellent frequency stability for uninterrupted comparison intervals up to 5 months.

The leading maintenance and longevity issues pertain to lamp and vacuum pump lifetime. Progress has been made on lamp fabrication, which now have a demonstrated lifetime of more than three years. Pump maintenance is accomplished without venting the main vacuum system, which should require no maintenance for at least 10 years. The control electronics are built from commercial products where feasible, and engineered subsystems are modular for easy replacement. In the near future, the same electronics will also be used with the new extended linear ion trap configuration currently under development which should greatly reduce the size of the standard and further improve long term stability.

The trapped ion frequency standard can operate with a variety of local oscillators (LO), including a quartz crystal, a cryogenic dielectric resonator oscillator, or a hydrogen maser. The LO currently used in stand-alone operation in the DSN is a BVA SC cut quartz crystal oscillator with a fractional frequency stability of 1.2×10^{-13} from 1 to 100 seconds. A time to analogue converter and integrator is used to generate the high resolution control voltage needed to steer the VCXO once each interrogation cycle (approximately 7 seconds). With a quartz crystal LO the JITS-4/VCXO fractional frequency stability passes into the 10^{-16} stability region at about 1 day. Stable output signals are provided to DSN users at 100 kHz, 1 MHz, 5 MHz, 10 MHz, and 100 MHz. Frequency stability, reliability, and sensitivity to perturbations will be presented.

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A MERCURY ION FREQUENCY STANDARD ENGINEERING PROTOTYPE FOR THE NASA DEEPSpace NETWORK*

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Abstract

An engineering prototype linear ion trap frequency standard ($1.1^{\circ}1'S-4$) using $^{199}\text{Hg}^{+}$ is operational and currently under test for NASA's Deep Space Network (DSN). The DSN requires high stability and reliability with continuous operation. For practical considerations optical pumping and atomic state selection are accomplished with a $^{202}\text{Hg}^{+}\text{RF}$ discharge lamp, and the trapped ions are cooled to near room temperature using a helium buffer gas. The standard is closely modeled from earlier research standards $1.1^{\circ}1'S-1$ and $1.1^{\circ}1'S-2$ which have demonstrated excellent frequency stability for uninterrupted comparison intervals up to 5 months. During an initial 135 day test in the DSN, $1.1^{\circ}1'S-4$ operated continuously using a quartz crystal as the local oscillator. Recent signal to noise measurements indicate that a short term stability of $\sigma_y(\tau) = 2.0 \times 10^{-14}/\tau^{1/2}$ can be achieved when operated with a sufficiently stable local oscillator.

Introduction

The NASA Deep Space Network (DSN) is used for communication and tracking, of a variety of spacecraft throughout the solar system. The complex consists of three Signal Processing Centers (SPC) located at Goldstone California, USA (SIT-10); Madrid, Spain (SPC-60); and Tidbinbilla, Australia (SPC-40). At all times, each station (which may consist of several antennas) operates from a single atomic frequency standard. For redundancy each station has four standards, two Smithsonian Astrophysical Observatory (SAO) hydrogen masers [16], and two Hewlett Packard cesium standards. Stability requirements range from less stringent needs for navigation, to the much more demanding needs of Very Long Baseline Interferometry (VLBI) and radio science experiments. The standards operate remotely from JPL, requiring that the clocks be transportable, operate autonomously, and be very reliable.

This paper reports on a program to develop an engineering prototype frequency standard for the DSN based on the 40.5 GHz ground state hyperfine transition of $^{199}\text{Hg}^{+}$ ions. Ions confined in a trap allow for long interrogation times and high

atomic line Q. Continuous operation is practical using a ^{202}Hg lamp to generate 194.2 nm radiation for atomic state selection [1] and helium buffer gas for ion cooling [2][3]. Long term stability is possible since the large 40.5 GHz $2S_{1/2}(F=0, m_F=0)$ to $2S_{1/2}(F=1, m_F=0)$ ground state hyperfine transition (Fig. 1) is less susceptible to magnetic and Doppler shifts in mercury than in lighter atoms. The linear ion trap provides a way to increase the detected fluorescence signal to noise (S/N) without increasing the second order Doppler shift [4]. The hyperfine transition is interrogated using Ramsey successive oscillatory fields with two 0.4 second microwave pulses separated by an interrogation time T_R ranging from 1 to 30 seconds.

The short term fractional frequency stability of the passive frequency standard can be expressed as

$$\sigma_y(\tau) = (2/\pi)(1/Q)(N/S)(T_c/\tau)^{1/2} \quad (1)$$

where τ is the averaging time, $Q = f_0/\Delta f$, Δf is the central Ramsey fringe width, $f_0 = 40.5 \text{ GHz}$, S = peak ion fluorescence, B = background light, $N = (S/2 + B)^{-2}$ and T_c the cycle time.

Several stability and environmental sensitivity measurements have been performed using earlier research standards $1.1^{\circ}1'S-1$ and $1.1^{\circ}1'S-2$ [5,6,7]. A short term frequency stability of $7 \times 10^{-14}/\tau^{1/2}$ has been measured and uninterrupted stability

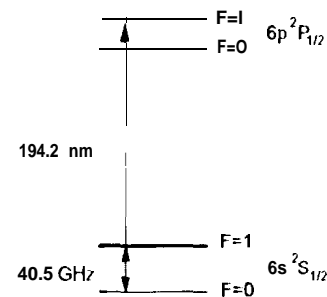


Figure 1: Simplified $^{199}\text{Hg}^{+}$ energy level diagram

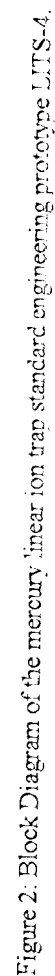


Figure 2: Block Diagram of the mercury linear ion trap standard engineering prototype LITS-4.

comparisons for averaging intervals up to 5 months made against a cavity compensated hydrogen maser referenced to NIST-UTC [8]. The standards, 1,1'1'S-1 and 1,1'1'S-2, have also been used extensively to examine operation, reliability and maintenance issues.

The engineering prototype, Linear Ion Trap Standard #/4 (1,1'1'S-4) is modeled closely from these earlier JPL research standards [4,5,6]. The design goals addressed the practical implementation issues of reliable continuous operation, transportability, and maintainability. The Shell term performance goal is to maintain S/N to achieve at least $\sigma_y(\tau) = 7 \times 10^{-14} / \tau^{1/2}$. Environmental isolation and electronic regulation requirements were derived from measurements with 1,1'1'S-1 and 1,1'1'S-2 [6]. The long term stability design goal is to achieve an average frequency drift rate of less than 1×10^{-16} / day, a factor of 30 improvement over hydrogen masers presently used in the DSN.

The Linear Ion Trap and Physics Package

The physics package contains the ion trap, optics, and vacuum, and magnetic bias coils. The trap operates at 1 MHz, and is the same size as earlier versions [4]. The entire trap and optics systems are surrounded by relatively large magnetic shields in a configuration similar to LITS-1 and LITS-2 [5,6]. The number of shields has been increased from three to five layers improving the longitudinal differential shielding from 800 (in 1,1'1'S-1) to 20,000.

Thermal control was incorporated into the physics package to control the temperature of the trap vacuum system, the magnetic shields and sensitive trap electronics to ± 0.1 °C. Thermal regulation is accomplished with a Thermo Electric Cooler (TEC) providing a thermal gain of greater than 20.

The LITS has stringent vacuum requirements with a required base pressure of about 1×10^{-9} Torr. The standard operates with a mercury background pressure of about 5×10^{-10} Torr and a helium pressure of about 10^{-5} Torr. Mercury vapor is generated by heating a small sample of HgO to about 200 °C. The helium buffer gas is introduced and stabilized by control of a heated quartz helium leak. Ions are generated by electron bombardment from an extended life lanthanum hexaboride cathode.

The main trap and vacuum system is designed to be service free for at least 10 years. For redundancy, dual electron source and ion gauge filaments are included. Vacuum pumps are on a valved manifold separate from the trap region to allow for pump maintenance. The valved manifold can accommodate two independent pumping systems consisting of either a turbomolecular forepump and/or an ion-getter pump combination. 1,1'1'S-4 currently operates with a

turbo-forepump system requiring a short maintenance period every two years. Electrical power to all of the heaters, filaments, and a vacuum isolation valve, is interlocked to the vacuum pressure as read by an ion gauge controller.

Electronics

A major focus of the engineering program was the development of reliable and stable electronics, for trap operation, microwave interrogation, and control of the Local Oscillator (LO). A block diagram of the electronic assemblies interfaced with the physics package is shown in Fig. 2. To minimize development time and cost, commercial electronics and components were used when feasible. Major commercial components include a VXI instrumentation system (includes IBASIC controller, counters, DAC, RS-232 communication, and multimeter), an ion gauge controller, 7 MHz synthesizer, monitor computer, and thermal controller.

Many electronic assemblies were also developed in our laboratory, including electronics specific to the trap and control of the local oscillator. To expedite development time, early concepts and breadboards were tested on LITS-1 and 1,1'1'S-2. Major trap electronics tasks included generation of stable trapping potentials, a filament driver for ion loading, current source for generating the operating magnetic field, the 40.5 GHz synthesis chain, and the lamp power-cooling system. Other major electronic assemblies developed were the main power supply, physics package thermal control, local oscillator control, and the RF distribution to the DSN. Smaller electronic assemblies were packaged in standardized modular enclosures and located in the physics package. Large electronic assemblies were made rack mountable and reside in an adjacent electronics rack. All electronic assemblies use standardized power, control, and monitor connections to allow for easy trouble shooting and maintenance changes. A more detailed description of the electronic requirements and engineered assemblies will be published elsewhere [14].

Interrogation Cycle Control and Monitor: The IBASIC controller in the HP VXI-B instrumentation system controls the clock interrogation cycle. A short program defines the operating and timing parameters for ion interrogation and determines corrections to keep the local oscillator on frequency with the ions. The program is slightly modified when different local oscillators are used.

A separate, inexpensive personal computer is used as a health and monitor system. Critical operating values (e. g. light counts, voltage levels, and LO frequency error values) are passed from the VXI to the monitor computer each measurement cycle (typically 7 to 12 seconds). Monitor data is written to the PC hard drive and available for FTP transfer to our laboratory for analysis. A capability to set alarm parameters and notify users of anomalous operation is also

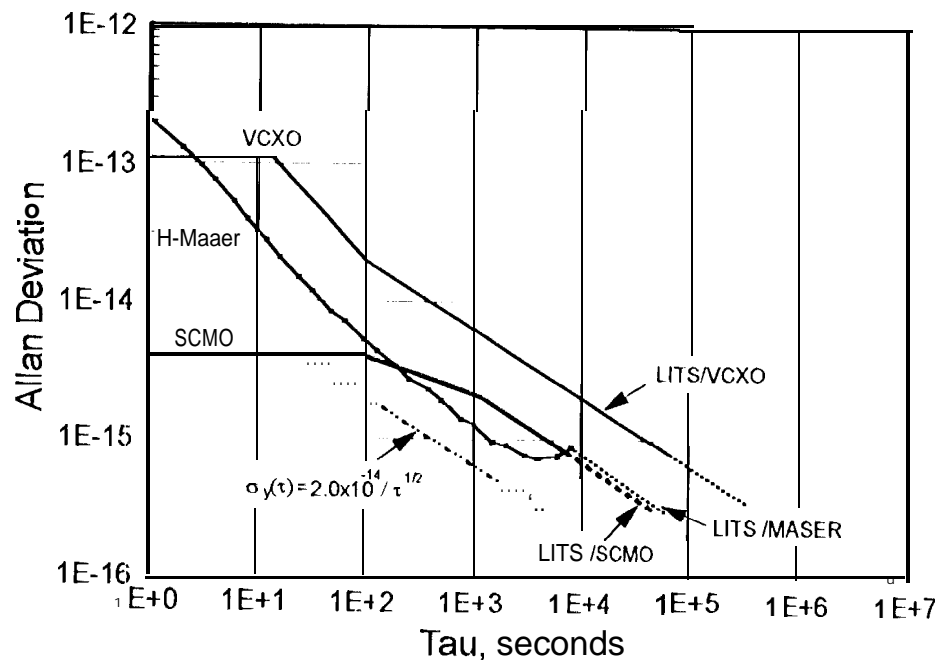


Figure 3: Allan 1 Deviation of the Hg+frequency standard using three different local oscillators, (a) a voltage controlled crystal oscillator VCXO, (b) a hydrogen maser, (c) a Superconducting Cavity Maser Oscillator.

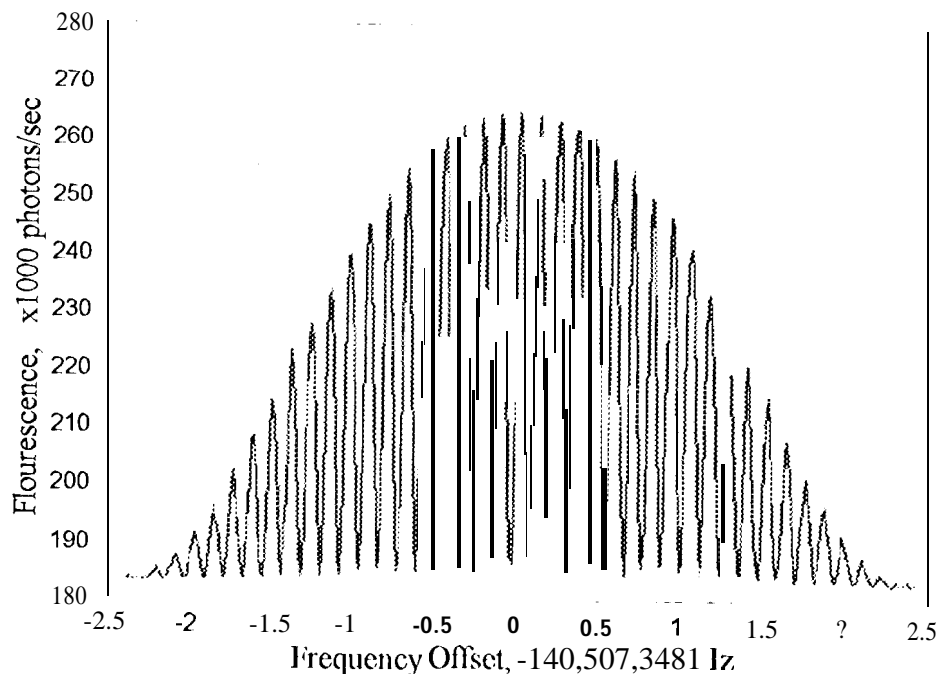


Figure 4: The 8 second Ramsey interrogation signal from the engineering prototype 1,1'1'S-4 (cycle time 12 seconds). This signal to noise and line Q correspond to a stability of $2.0 \times 10^{-14} / \tau^{1/2}$

included. For reliability, there is no handshaking between the VXI and the monitor computer.

Local Oscillator Control: The performance of the Local Oscillator (L.O.) plays an important role in the achievable performance with a passive atomic frequency standard [11]. Most of the earlier characterization of trapped ion frequency standards was performed using hydrogen maser[s] for the local oscillator, though quartz crystal and superconducting dielectric resonators have also been used [4,12]. The engineering prototype has the capability of interfacing to any of these L.O.'s and the interrogation cycle and L.O. attack time is optimized for each L.O. with software. Either the quartz crystal or a H-maser suffice as a local oscillator for continuous operation. Presently, the 4 Kelvin cryogenic dielectric resonators operate unperturbed only as long as the helium Dewar hold time.

Figure 3 shows the expected performance of a trapped mercury ion standard operating with S/N corresponding to a stability of $7 \times 10^{-14}/\tau^{1/2}$ using three different local oscillators, a VCXO, a hydrogen maser, and a Superconducting Cavity Maser Oscillator (SCMO). With a VCXO, the short term stability and steering algorithm can greatly impact the stability [11]. For times longer than 10^5 seconds, the achievable stability will be determined almost exclusively by the LITS. A similar though smaller degradation results from using a hydrogen maser as the L.O. Depending on the short term stability of the maser, the trapped ion performance of $7 \times 10^{-14}/\tau^{1/2}$ can easily be degraded to $1 \times 10^{-13}/\tau^{1/2}$. With an SCMO as the L.O. [12] the full short term stability of the LITS can be characterized.

For stand alone operation LITS-4 uses a state of the art BVA SC cut 5 MHz VCXO as the local oscillator. Multiplication and division of the VCXO output provides the required distribution frequencies to the DSN at 0.1, 1.5, 10, and 100 MHz. One of the 100 MHz outputs provides the source signal for the multiplication chain up to 40,507,347,996,8xx GHz to interrogate the ions. The VCXO is steered after each ion interrogation cycle in a frequency lock loop to track the ion atomic line. The high resolution voltage control of the quartz crystal oscillator is accomplished with the use of Time to Analogue Converter (TAC) consisting of a commercial pulse generator and a current integrator [13]. This technique allows steering the VCXO with a minimum correction step of 1×10^{-17} , yet provides the range to steer the VCXO for more than 5 years without adjustment.

Initial Operational Experience

Initial characterization and operation of LITS-4 in our laboratory was performed using a hydrogen maser as the L.O. A signal to noise ratio was achieved to produce the desired performance goal of $7 \times 10^{-14}/\tau^{1/2}$. Recently, further

optimization of lamp operation has produced a very large S/N at an interrogation time of only 8 seconds. Figure 4 shows the 40,507,347,996,8xx GHz microwave signal that using Eq. 1 predicts a short term stability of $2.0 \times 10^{-14}/\tau^{1/2}$. For reference this performance is shown as a dashed line in figure 3. Two LITS standards using cryogenic dielectric resonator L.O.'s will be required to directly measure this performance.

Initial Experience in the DSN with a crystal oscillator

For early operational experience in the DSN environment, the engineering prototype LITS-4/VCXO was moved to the Goldstone, CA DSN complex (SPC-10) in September 1995 and operated continuously until it was returned to our test laboratory in February 1996. Operation was briefly interrupted for one day in November due to a scheduled power shutdown.

During shipping, to SPC-10, the vacuum system valves were closed and the pumps were off for approximately 9 hours while it was transported to the station. (previous standards have been valved off for weeks with no significant consequences to startup performance). Total time to re-cable the physics package to the electronics rack, power up, acquire the microwave signal, and put the VCXO on frequency was about 3 hours. The standard takes about 48 hours to come to thermal equilibrium and the best long term stability ($< 1 \times 10^{-16}/\text{day}$) can be achieved in approximately 10 days. During this 135 day test stability comparisons were performed on an intermittent basis between the LITS-4 and an SAO hydrogen maser using temporary measurement hardware external to the LITS standard. For part of the 135 day duration the LITS-4/VCXO 5 MHz output was connected to a TurboRogue GPS receiver for comparisons to other standards located around the world [15].

Operating parameters such as ion fluorescence, voltage, and temperature levels were examined observed daily in our laboratory in Pasadena, California. Sixty-four channels of data were collected by the monitor computer each interrogation cycle and saved into one hour files. These files were transferred to JPL daily via the Internet. Stability data from the temporary measurement system were also gathered remotely. Figure 5 shows the measured stability between LITS-4/VCXO and the VLG-11 hydrogen maser SAO-15 [16] for a 10 day interval. The short term performance shown results from the available quartz crystal L.O. and the first order steeling-loop [11]. For averaging times longer than 40,000 seconds the observed long term stability is due to the drift of the SAO hydrogen reference maser [8]. Figure 5 also shows the stability comparison with the linear component of the maser drift removed.

Before the DSN test, the only characterization of LITS-4/VCXO against a second LITS standard is shown in

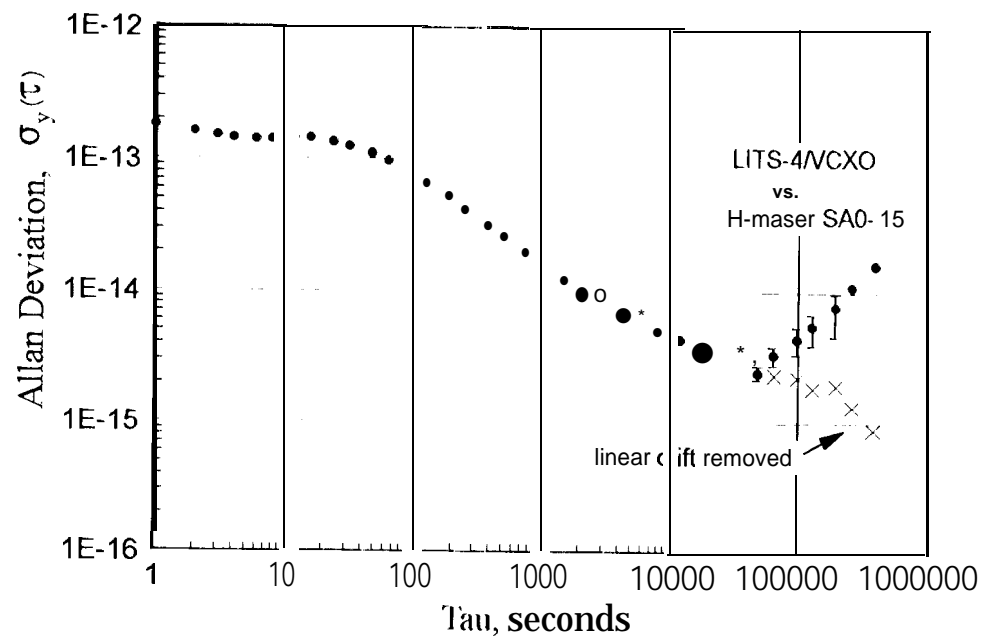


Figure 5: LITS-4/VCXO vs. SA0-15 J Hydrogen Maser at the DSN station SPC-10

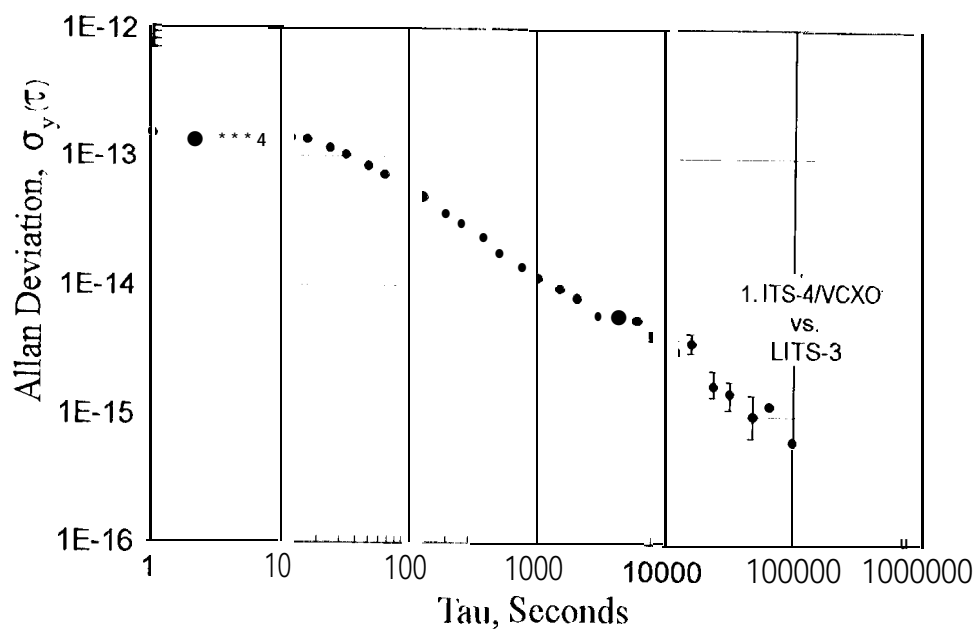


Figure: 6 LITS-4(1.O=VCXO) vs. LITS-3(1.O=H-maser)

Figure 5. This 3 day comparison against 1,1'1'S-3 (using an 1 l-maser L(O) [20] shows the stability of the crystal 1,0 based 1,1' 1'S-4 passing into the 10^{-16} decade at about a day.

Environmental Sensitivity

A full characterization of the 1,1'1'S-4 environmental sensitivity and optimization of operation parameters is currently being performed. The four largest frequency offsets [6] are 1) the magnetic field shift, 2) the 2nd Order Doppler shift (due to thermal and driven ion motion), 3) a smaller Helium pressure shift, and 4) a very small light shift due to the presence of some light from the discharge lamp dim state during microwave interrogation.

In the present physics package configuration, the magnetic shielding is sufficient to reduce external fluctuations by 20,000. At the current "high field" operation of 50-80 mG the sensitivity to external fluctuations is $2 \times 10^{-17}/\text{mG}$. All efforts were made to eliminate possible stray currents or ground loops. The vacuum pumps are isolated from the trap vacuum with a glass break. Future versions of the physics package [18,5] will operate at much lower magnetic fields reducing field sensitivity even more.

The second order Doppler shift will most likely be the current limitation to very long term stability. Long term stability requires the ion number (and temperature) to be kept stable over the length of the averaging interval. The ion number depends on operating parameters, trap well depth, ion load and loss rate, and the condition of the vacuum. The electron current used to ionize ^{199}Hg atoms and the temperature of the 11P(O) source are regulated. The aging of the vacuum system or changes in the Hg pressure as a function of 11gO temperature over time are not controlled. The longest continuous stability measurement to date in this "open loop" operation is the 5 month comparison between 1,1'1'S-2 and a cavity compensated hydrogen maser STSC-1 [17][8]. Over this 5 month interval the relative long term drift was measured to be $2.1 (0.8) \times 10^{-17}/\text{day}$. Because of improved shielding and electronic stability the engineering prototype 1,1'1'S-4 should produce a long term stability better than 1,1'1'S-2.

Thermal Sensitivity Anomaly: The frequency sensitivity to thermal variations in the earlier research LITS-1 and LITS-2 with no thermal regulation was about $-1 \times 10^{-14}/^\circ\text{C}$. Initial thermal sensitivity measurements with 1,1'1'S-4 showed the thermal sensitivity to be as high as $5 \times 10^{-14}/^\circ\text{C}$ (with the TEC off), almost an order of magnitude higher and the sign opposite than expected.

Early operation of 1,1'1'S-4 was set up to maximum the detected signal to noise ratio. The source of the higher than expected thermal sensitivity can be seen in Fig. 7 which shows the thermal sensitivity correlated with the signal size.

As the trapping potential is changed, the well depth, and therefore the ion density and temperature come to a new equilibrium. For very large ion clouds, small variations in ion number (due to varying load and loss rates, resulting from a vacuum wall temperature change) can have a larger effect, than the same variations for a few ions along the trap axis. Figure 7 shows the signal size as a function of RF trapping potential expressed as a calculated Allan deviation for the 8 second interrogation time. At an operating value of 175 Vrms, high performance of $\sigma_y(\tau) = 2 \times 10^{-14}/\tau^{1/2}$ is associated with a thermal sensitivity of $5 \times 10^{-14}/^\circ\text{C}$. For most applications, this frequency performance is totally masked by limitations of the local oscillator, so by operating at a lower well depth, e.g. 110 Vrms, we can still maintain a performance of $\sigma_y(\tau) = 5 \times 10^{-14}/\tau^{1/2}$ with a thermal sensitivity below $1 \times 10^{-14}/^\circ\text{C}$. This unregulated sensitivity is about the same as the fully regulated sensitivity of the best hydrogen masers currently in the USN. These masers require thermal regulation to 1 (0) microKelvin. The LITS improvement in long term stability by a factor of 30 can be achieved with long term thermal regulation of only 0.1 $^\circ\text{C}$.

Reliability and maintainability

The electronics are commercial or modular and easy to replace if necessary. The standard operates continuously with a physics package that should require no vacuum openings for 10 years. Turbopump maintenance will need to be performed on about a two year interval to lubricate the main bearing, or alternatively to switch to a second pumping system attached to the manifold.

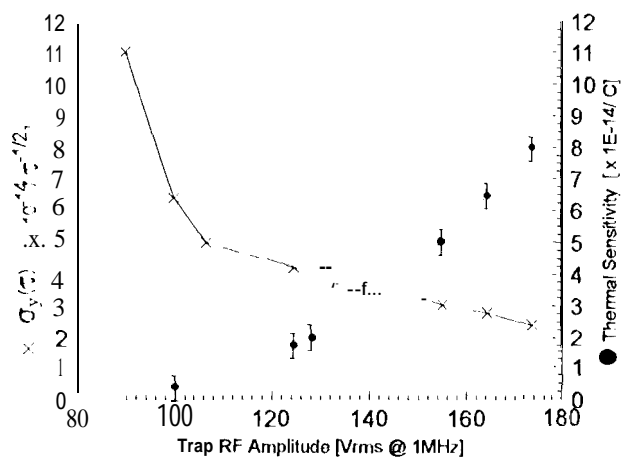


Figure 7: Thermal Sensitivity of the uncontrolled 1,1'1'S-4 physics package as a function of trapping potential. Also shown is the Allan Deviation based on signal size changes.

The lamp may require periodic adjustment or replacement. A lamp lifetime of more than 3 years was achieved in 1,1'1'S-2, though the lifetime can be significantly reduced by improper fabrication. Long lamp life is correlated to quartz quality, cleanliness, and most importantly, ²⁰²Hg pressure. Presently, the power to the lamp is switched between two modes (bright and dim), requiring thermal equilibrium parameters to be finely tuned for proper operation. Since the 170 MI Hz lamp driver amplifier is itself thermally sensitive, the thermal environment at the electronics rack must remain in a 6 degree window for the lamp level. For operation out of this temperature range the lamp power levels would require a small adjustment to maintain proper switching. All of the standards operate in a good thermal environment in the 1 DSN, though a different 170 MI Hz amplifier with lower thermal sensitivity may be included in future versions to make lamp operation more robust to large thermal changes in the environment.

Future Physics Package Upgrade

An Extended Linear Ion Trap (ELIT) has been under development in our lab for the last two years [18,19]. This linear ion trap consists of two regions, a magnetically shielded region for microwave interrogation, and a separate region for ion loading and interrogation with 194 nm light. Ions are "shuttled" back and forth between these two regions with 1X potentials. There are a number of advantages of this configuration. Practical advantages are the standard can be smaller, lighter, and lower cost. The major maintenance advantage is that the lamp and photomultiplier tubes can be accessed without opening the magnetic shields. Performance advantages, especially towards further improvements of long term stability and accuracy should result from operating at reduced ion densities during microwave interrogation. Increased magnetic homogeneity will also allow operation at lower fields.

Initial results from a research version of the 1,1'1'1 configuration produced equivalent signal to noise as with the current LITS standards [8, 19]. Longer term stability characterization is in progress. An engineering prototype "1,1'1'1" replacement for the LITS physics package is being designed to be exchangeable with the current configuration and will use the same electronics assemblies developed for the engineering prototype.

Conclusions

A mercury linear ion trap frequency standard engineering prototype, LITS-4, has been developed for continuous operation and tested in the NASA Deep Space Network. Measured signal to noise, and atomic line Q indicate that 1,1'1'S-4 could achieve a short term stability performance of

$\sigma_y(\tau) = 2 \times 10^{-14} / \tau^{1/2}$ when operated with an appropriate local oscillator.

The trapped ion frequency standard can operate with a variety of local oscillators (LO), including a quartz crystal, a cryogenic dielectric resonator oscillator, or a hydrogen maser. The LO currently used in stand-alone operation in the 1 DSN is a 13VASC cut quartz crystal oscillator with a fractional frequency stability of 1.2×10^{-13} from 1 to 100 seconds. A time to analogue converter and integrator are used to generate the high resolution control voltage needed to steer the VCXO. With a quartz crystal LO the LITS-4/VCXO fractional frequency stability passes into the 10^{-16} stability region at about 1 day.

The leading maintenance and longevity issues pertain to lamp and vacuum pump lifetime. Progress has been made on lamp fabrication, which now have a demonstrated lifetime of more than three years. Vacuum pump maintenance of 1,1'1'S-4 can be accomplished without venting the main vacuum system, which should require no openings for at least 10 years. The control electronics are built from commercial products where feasible, and engineered subsystems are modular for easy replacement.

The same electronics will also be used with the new extended linear ion trap configuration currently under development. This alternative physics package configuration will offer a number of advantages including reduced size and cost, easier maintenance, and operation at reduced ion densities. This last feature will be a key in achieving further improvements to long term stability and accuracy.

*This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.